THE EFFECTS OF AMBIENT CONDITIONS ON CESIUM CLOCK RATES

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ABSTRACT

The rates and errors of 42 cesium clocks in 6 different vaults at USNO were studied using 18 months of hourly data. Temperature effects were found to be negligible when the temperature was controlled to within ±1°C. During excursions much greater than this, rate changes in either sense are possible. No short-term humidity effects were evident, but there appears to be an annual variation in clock rates (in either sense) dependent on absolute humidity. Significant intercorrelations between clocks indicate the general importance of environmental conditions of some kind.

INTRODUCTION

It is well known that the rates of cesium-beam atomic clocks are susceptible to changes in environmental conditions, necessitating their operation under controlled conditions. Iijima et al.[1] measured the temperature, humidity, and atmospheric pressure dependence for one clock in an environmental chamber, as well as the effect of rotating the clock relative to the earth's magnetic field. Dorenwendt[2] and Bava et al.[3] found annual variations in PTB and IEN clocks, respectively, that appear to be related to humidity and, perhaps, temperature. Other factors affecting clock rates are power fluctuations and vibrations[4,5].

Dorenwendt[2] and Guinot[6] have noted seasonal variations in the USNO timescale relative to PTB and TAI, respectively, that they attribute mainly to USNO. Boulanger et al.[7] and Allan[8] found seasonal variations in the timescale of PTB, but none in that of USNO.

The current study was undertaken to investigate the effects of ambient conditions on the clocks comprising the USNO timescale and their connection to seasonal variations, if any, in that timescale.

DATA

The data consisted of 18 months of hourly clock rates for each of 42 commercial cesium standards in 6 different vaults at USNO, as well as temperature and relative humidity measurements for each vault between MJDs 46437 and 46977. The absolute humidity was computed from the temperature, relative humidity, and Figure 15 in [1].

The clocks were restricted to those that were weighted, i.e. that contributed to the USNO timescale, in order to be certain that we were dealing with well-known and well-behaved clocks. The data were divided into 18 sets of 30 days each, hereafter referred to as "months". During an average month, data were available from 24 clocks.

ENVIRONMENTAL ANALYSIS

Statistical regressions were performed between all of the following independent (x) and dependent (y) variables:

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x	y
hourly temperature gradient	hourly rate change
hourly relative humidity gradient	hourly rate change lagged 2 hours
hourly absolute humidity gradient	hourly rate change lagged 4 hours
preceding-6-hour moving average	6-hour square root of Allan variance
	of each of the above

A 6-hour moving average was tried in order to look for smoothed effects due to buffering by the clock casing. Lags of 2 and 4 hours were used in order to find any delayed effects on the rate, as might occur from secondary internal temperature effects due to variations in power dissipation induced by changes in environmental conditions. Square roots of the Allan variance were computed for (moving) 6-hour durations as a test for short-term effects on the noise.

TEMPERATURE EFFECTS

The average linear correlation coefficients for temperature gradient are summarized in Table 1, sorted by either vault or model. A Student's t-test (or a goodness-of-fit F test) gives 0.07 as the lower limit on the significance of the absolute value of the correlation coefficients at a confidence level of 90%.

No vault or model average is significant, and the only averages that were significant were for 2 individual clocks for 0-lagged rate changes. These negative results are not surprising, since Iijima et al.[1] determined a temperature coefficient of $-1.96\times 10^{-14}/^{\circ}$C for one clock over a range of 5 deg C. The temperatures of USNO vaults are generally maintained to within $\pm 1^{\circ}$C, so temperature variations should not cause rate changes near a typical daily clock error of 5 parts in 10^{14}. The range in temperature our clocks undergo is simply insufficient to permit accurate determination of the temperature dependence of their rate changes.

In order to investigate the influence of extreme temperature excursions, instances of air conditioning failure were examined. During one such failure in the Building 1 vault, the temperature increased 6°C twice over an 8.8-day period (Figure 1). As a result, 8 out of the 9 clocks therein experienced significant rate changes. Of the 5 clocks that had been contributing to the USNO timescale, 1 was excluded; of the other 4 deemed sufficiently accurate to remain in the timescale, the 2 clocks whose frequences are depicted in Figure 1 represent the opposite extremes of rate change. The first clock responded to the temperature change immediately, and increased in rate, while the second one showed a delayed (by 5 days) and prolonged (by 50%) response in the opposite sense. During this air conditioning failure and a similar one in each of the other 2 main vaults, the responses of 70% of 20 clocks were immediate, like that of the first clock in Figure 1, but 55% were in the direction of the second clock; 20% showed no response at all.

The temperature sensitivity of cesium clocks is primarily due to the sensitivity of the power-regulating step-recovery diode in the harmonic generator[9].

HUMIDITY EFFECTS

The average correlation coefficients for the relative humidity and absolute humidity gradients are listed in Tables 2 and 3 respectively. Not only is no vault or model average significant, but no individual clock's is either.

The humidity in USNO vaults is generally not controlled. Iijima et al.[1] found an absolute humidity coefficient of $-0.71\times10^{-14}/(\mathrm{gm}^3)$ for one clock. Probably the only way humidity could influence a cesium clock is through a change in heat conduction inside the clock,

which would affect the temperature-sensitive step-recovery diode[10].

In a search for long-term effects of ambient conditions, the temperature and absolute humidity in the Building 1 vault over the 18 months were compared with the frequencies of 5 clocks therein relative to UTC (Figure 2). An annual variation, probably related to the humidity, is evident, confirming the results of Dorenwendt[2] and Bava et al.[3]. As they found, even the sense of the effect varies from clock to clock. In each of our cases, there is a lag of about 60 days. Frequency plots relative to UTC (USNO) are very similar, indicating that the effects vary from vault to vault. Linear correlation coefficients for the temperature are significant for only 1 clock, but for the humidity, they are significant for all but 1 clock. The spike at MJD 46809 is due to the temperature glitch in Figure 1. The spikes at MJD 46619 for HP# 0653 and at MJD 46699 for HP# 2100 correspond to failures in continuous operation.

CLOCK INTERCORRELATION

In an effort to detect similar behavior by the clocks that might be attributed to ambient conditions, regressions were performed between the hourly rate changes of every clock pair. The linear intercorrelation coefficients, averaged over the 18 months, ranged from -0.103 to 0.399 and, over all the clocks, averaged 0.218±0.004. Of the 670 intercorrelations, 90% exceeded the minimum significance level of 0.07, so some ambient conditions certainly affect clock rates generally.

The intercorrelations are sorted by vault in Table 4. There is no clear indication that clocks in the same vault behave any more similarly than clocks in different vaults. However, the highest correlations are among those clocks in Buildings 16 and 52, which are in prefab environmental chambers with temperature control twice as good as that in the basement vault of Building 1. It might thus be inferred that small temperature variations contribute more to the noise than to systematic differences between clocks.

In a given vault, there was no significant dependence of clock intercorrelation upon separation. The clocks range from 0.2 m to 3.6 m apart and are on stable platforms, but are not otherwise shielded from electromagnetic interference or vibrations.

The intercorrelations are sorted by model in Table 5. The J45-option (high-performance, high-stability-tube) clocks behave significantly more alike than the 004-option (high-performance-tube) clocks, presumably because of their greater stability.

CONCLUSIONS

As long as the temperature control in USNO vaults is maintained to within ±1°C, there are no significant temperature effects in the cesium clock rates, certainly none than can be modelled and removed *in situ*. The same is true for humidity effects over times of the order of hours or days, but there apparently is an annual variation in the clock rates related to absolute humidity. This may explain seasonal variations in the USNO timescales. Large temperature and humidity excursions may either accelerate or decelerate the rate of a clock. Significant intercorrelations between USNO clocks indicate the general importance of ambient conditions of some kind.

Improvements in the environmental stability of USNO clock vaults are continuing to be made. Further studies will be made to determine and, if possible, remove humidity effects, as well as to evaluate the importance of vibrations, clock age, differential clock weighting, and type of timescale algorithm.

ACKNOWLEDGMENTS

The author wishes to thank Louis Kalikow for helping with the preliminary data analysis.

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Table 1

Linear correlation coefficients between temperature gradient $\dot{T}$ and its preceding-6-hour moving average $<\dot{T}>$ on the one hand and hourly changes (lagged 0, 2, and 4 hours) and 6-hour square roots of the Allan variance on the other, averaged over all clocks and over 18 months, for the 3 main USNO clock vaults and for the 2 principal models of USNO clocks. Here and elsewhere, the standard errors (in parentheses in units of 0.001) reflect only the month-to-month variation of the average coefficients.

	Rate Changes				Sq. Root of Allan Var.
	Lag 0		Lag 2	Lag 4	
	$\dot{T}$	$<\dot{T}>$	$\dot{T}$	$\dot{T}$	$\dot{T}$
Vault:					
Bldg. 1	0.010(7)	0.000(5)	0.010(8)	0.005(8)	-0.002(2)
Bldg. 16	0.037(6)	0.007(5)	0.003(5)	0.000(6)	0.001(1)
Bldg. 52	-0.010(8)	-0.006(5)	-0.005(4)	0.005(6)	-0.001(3)
Model:					
HP5061A/004	0.020(4)	0.001(4)	0.007(4)	0.004(4)	-0.001(2)
HP5061A/J45	0.007(6)	0.002(4)	-0.001(5)	0.002(4)	0.000(5)

Table 2.

Same as Table 1, but for the relative humidity gradient H.

	Rate Changes				Sq. Root of Allan Var.
	Lag 0		Lag 2	Lag 4	
	$\dot{H}$	$<\dot{H}>$	$\dot{H}$	$\dot{H}$	$\dot{H}$
Vault:					
Bldg. 1	-0.014(8)	-0.004(5)	-0.012(7)	-0.002(8)	0.004(3)
Bldg. 16	-0.001(1)	0.003(2)	0.020(5)	0.007(2)	0.016(7)
Bldg. 52	0.001(8)	-0.000(3)	0.008(5)	0.010(6)	-0.006(10)
Model:					
HP5061A/004	-0.009(5)	-0.004(3)	-0.003(6)	0.001(6)	0.001(5)
HP5061A/J453	0.000(6)	0.004(4)	-0.003(5)	0.006(6)	0.001(8)

Table 3.
Same as Table 1, but for the absolute humidity gradient A.

	Rate Changes				Sq. Root of Allan Var.
	Lag 0		Lag 2	Lag 4	
	$\dot{A}$	$\langle\dot{A}\rangle$	$\dot{A}$	$\dot{A}$	$\dot{A}$
Vault:					
Bldg. 1	-0.012(8)	-0.004(5)	-0.007(6)	0.003(8)	0.003(3)
Bldg. 16	0.027(7)	0.005(3)	0.002(2)	-0.008(1)	0.018(6)
Bldg. 52	0.004(7)	-0.001(3)	0.008(6)	0.012(6)	-0.008(10)
Model:					
HP5061A/004	-0.004(5)	-0.004(3)	-0.002(5)	0.004(5)	-0.000(4)
HP5061A/J453	0.002(6)	0.004(4)	-0.002(6)	0.011(7)	-0.002(8)

Table 4.
Linear correlation coefficients between hourly rate changes of clocks in the 3 main USNO vaults, averaged over all clock combinations and over 18 months. In an average month, Buildings 1, 16, and 52 con- tained 10, 9, and 5 weighted clocks respectively.

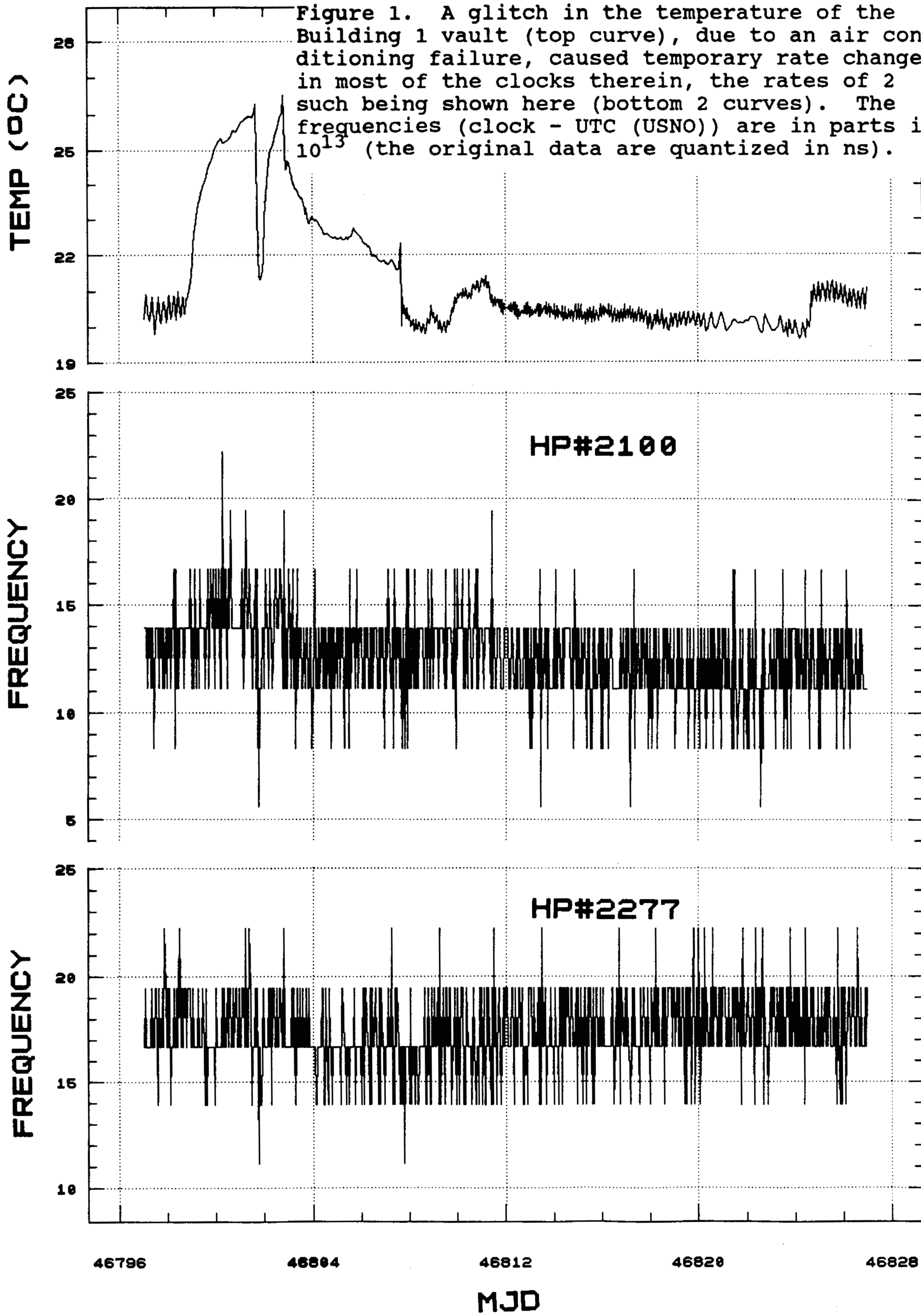
Vault:	Bldg. 1	Bldg. 16	Bldg. 52
Bldg. 1	0.194(10)	0.209(6)	0.217(7)
Bldg. 16		0.234(5)	0.241(6)
Bldg. 52			0.260(13)

Figure 5.
Linear correlation coefficients between hourly rate changes for the 2 principal models of USNO clocks, averaged over all clock com- binations and over 18 months.

Model	HP5061A/004	HP5061A/J45
HP5061A/004	0.208(7)	0.257(4)
HP5061A/J45		0.328(14)

Figure 1. A glitch in the temperature of the Building 1 vault (top curve), due to an air conditioning failure, caused temporary rate changes in most of the clocks therein, the rates of 2 such being shown here (bottom 2 curves). The frequencies (clock - UTC (USNO)) are in parts in 10^{13} (the original data are quantized in ns).

Figure 2. The temperature and humidity in the Building 1 vault (top 2 curves) over 18 months are compared here with the rates of 5 clocks therein. All points are 10-day averages. The frequencies (clock - UTC) are in parts in 10^{13}.



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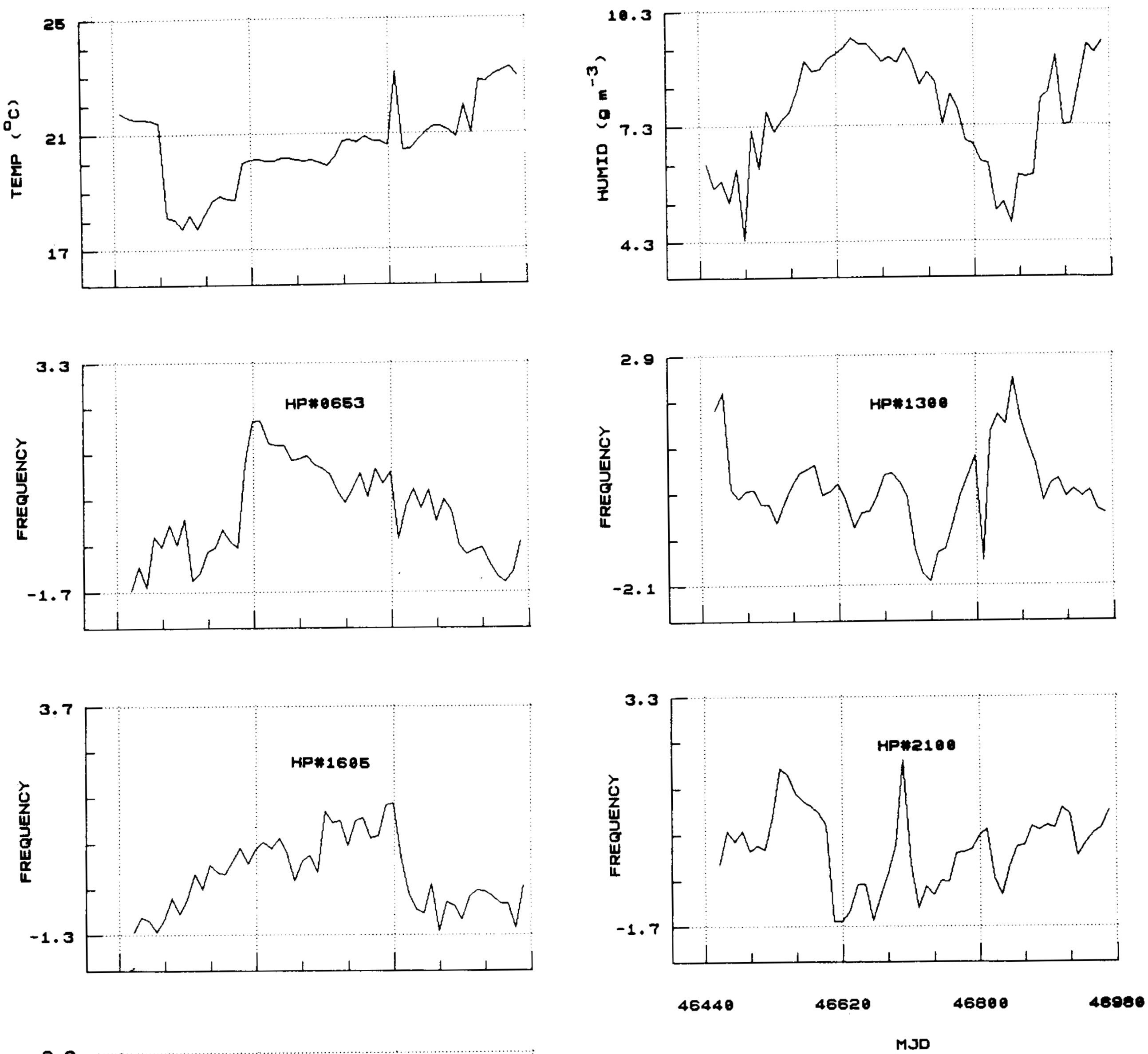

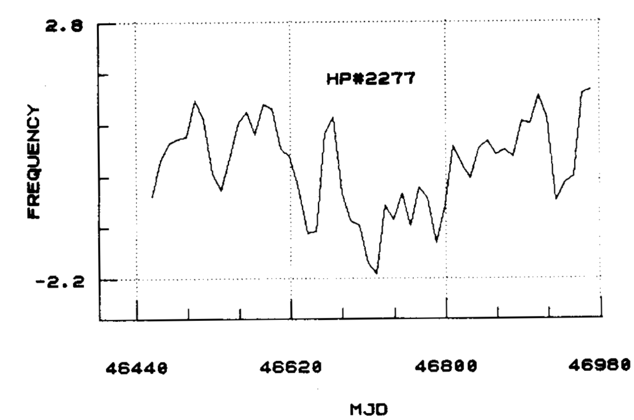

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QUESTIONS AND ANSWERS

Frank Leslie, Harris Corporation: During the times that this data was gathered, were there recordings made of barometric pressure?

Mr. Breakiron: Unfortunately, no.

David Allan, National Bureau of Standards: Some of your previous data, I remember, you saw some correlation with voltage. Did you investigate that any further?

Mr. Breakiron: No, there hasn't been any that I am aware of. That would affect the internal temperature of the clock, which was not my concern here.

Edward Mattison, Smithsonian Astrophysical Observatory: Was this work prompted by your observing changes in the clock rates that look systematic, or was it just an investigation to find out if these effects exist? in other words, how do you observe effects that look like they are systematic?

Mr. Breakiron: It was an investigation to see if the effects occur. We had a lot of data that is not generally easily obtainable.